Various Sources of PM_{2.5} and their Impact on the Air Quality in Tainan City, Taiwan

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ABSTRACT

The recent deterioration of Taiwan's air quality is partly due to fine particulate matter (PM_{2.5}). With several studies pointing out a direct link between PM_{2.5} and the global disease burden, plans are underway to reach the standard of an annual average PM_{2.5} concentration of 15 $\mu\text{g m}^{-3}$ in Taiwan by 2020. Subsequently, environmental protection bureaus in all cities should assess PM_{2.5} emission sources and implement control strategies. This study focuses on analysis of PM_{2.5} sources within Tainan City in an effort establish the contribution of large-scale pollution sources within the city as well as those from neighboring counties and cities. During this study, the top nine largest emission sources in Tainan City were investigated: (1) the Chemical manufacturing industry, (2) the iron and steel industry, (3) the power industry, (4) manufacturing of coal-based products, (5) diesel vehicles, (6) two-stroke scooters, (7) catering, (8) construction/road dust, and (9) open burning. Three important pollution sources in the central region of Taiwan were investigated as well, including: (1) the Taichung Power Plant, (2) the Formosa Petrochemical Corporation (FPCC) Sixth Naphtha Cracking Industry, and (3) the Dragon Steel Company in Taichung City, Changhua County, and Yunlin County, respectively, all of which are located on the windward side of Tainan City. The Community Multiscale Air Quality Model (CMAQ) was used to simulate the impact of the mentioned sources on Tainan's air quality. The results for the monthly contributions from the different sources averaged over a one year period indicated that diesel vehicles are the largest source, emitting up to 1.06 $\mu\text{g m}^{-3}$, followed by the Taichung Power Plant, which had 0.87 $\mu\text{g m}^{-3}$ the construction industry and road dust emissions, with 0.80 $\mu\text{g m}^{-3}$, and with open burning of waste having the lowest contribution. These results can be applied to facilitate the development of follow-up air quality control strategies.

Keywords: Emission source; Different pollution sources; Tainan City; Air quality model (CMAQ); PM_{2.5}.

INTRODUCTION

In recent years, Taiwan's air quality has been seriously affected by fine particulate matter (PM_{2.5}). As illustrated in many studies, fine particulate matter is a great danger to human health since it causes lung-related diseases (Betha and Balasubramanian, 2018; Chen *et al.*, 2018). Therefore, Taiwan's Environmental Protection Administration (EPA) has stipulated a standard whereby the annual average PM_{2.5} concentration is 15 $\mu\text{g m}^{-3}$, and the 24-hour average is 35 $\mu\text{g m}^{-3}$ (Lee *et al.*, 2016; Betha and Balasubramanian, 2018). In order to achieve this goal for the annual average PM_{2.5} concentration in every county and city by 2020, the

respective environmental protection bureaus (EPBs) must estimate the impact of pollutant emissions and implement applicable air pollutant control strategies (Yang *et al.*, 2017a; Wang *et al.*, 2018). This study focuses on Tainan City and targets substantial pollution sources within the jurisdiction and significant large-scale pollution sources in the neighboring counties and cities (Zhou *et al.*, 2017; Kim and Lee, 2018). A simulation was carried out in order to understand the impact of various pollution sources on the city's ambient air (Byun and Schere, 2006; de Almeida Albuquerque *et al.*, 2018).

According to the Taiwan Emission Data System (TEDS) version 9.0, classification of the emission sources was done based on the industry category. Nine large industrial emission sources in Tainan City were selected: (1) the chemical manufacturing industry, (2) the iron and steel industry, (3) the power industry, (4) manufacturing of coal-based products, (5) diesel vehicles, (6) two-stroke scooters, (7) catering, (8) construction/road dust and (9) open burning (Provencal *et al.*, 2017). The model is intended to explore industries

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having the most serious impact in terms of pollution on Tainan City. Due to the characteristics of air circulation and dominant wind directions within Tainan City, three counties in the central region of Tainan were also investigated as well (Chuang *et al.*, 2017). The impact of notable $PM_{2.5}$ sources in the industrial zones, i.e., the Taichung Power Plant, the Formosa Petrochemical Corporation (FPCC), the Sixth Naphtha Cracking Industry, and the Dragon Steel Company were examined as well (Lu *et al.*, 2016; Sekiguchi *et al.*, 2018).

The Community Multi-scale Air Quality Model (CMAQ) version 5 was used for multiple case simulations to analyze $PM_{2.5}$ concentrations during the winter, spring, summer, and autumn seasons, which were represented by January, April, July, and October 2013 (Mebust *et al.*, 2003). The annual average was evaluated using the average of the months under investigation and then the resultant data was used to explore the changes in air quality of Tainan City as a result of emissions from different industrial categories of $PM_{2.5}$, NO_x , SO_2 , NH_3 , and NMHC (Betha and Balasubramanian, 2018; de Almeida Albuquerque *et al.*, 2018). Even though the CMAQ model has been applied to predict the air quality elsewhere, there is currently no study to the author's knowledge that has applied the model to predict the ambient air quality in Tainan and the effects of significant sources of $PM_{2.5}$ from neighboring cities and counties. Information from this study can thus be applied in developing strategic plans towards improving the ambient air quality in Tainan City.

METHODOLOGY

Domain and Grid Resolution of the Model

In this study, the U.S. EPA's latest air quality model

CMAQ was used as a simulation core module for conducting the analysis. In order to achieve high-accuracy simulation results, the CMAQ nest simulation function was used, whereby large grid simulation results provided hourly data for the small grid simulation (Byun *et al.*, 1998; San José *et al.*, 2003). The nested technology grid nesting design ratio was 1:3, and the first layer of the coarsest grid ($81\text{ km} \times 81\text{ km}$) effectively covered the required simulation area in East Asia (Zhang *et al.*, 2007). The coarsest grid could therefore be applied to explore the transmission phenomenon of air pollutants in East Asia (Punger and West, 2013). After three nested simulations, the fourth layer $3\text{ km} \times 3\text{ km}$ simulation range shown in Fig. 1 was reached, with which the air quality in northern, central, or southern Taiwan can be explored (Byun and Schere, 2006).

Numerical Analysis

Model Inputs, Pre-processing of Meteorological Data and Boundary Conditions

Prior to a simulation, appropriate pre-meteorological processing, pre-emission data processing, initial and boundary conditions, etc., are required in order to generate appropriate meteorological, emissions, and initial field concentrations, as well as appropriate boundary conditions (Byun and Schere, 2006). The meteorological pre-processing program used in this study utilized 3D mesh meteorological data simulated using the WRF (the Weather Research and Forecasting Model), and outputted the meteorological input data required by the CMAQ through the pre-metamodel processing program (Wong *et al.*, 2012; de Almeida Albuquerque *et al.*, 2018). The required data for anthropogenic and biological emission sources together with their respective databases are provided in Table 1, where for East Asia, anthropogenic emissions were obtained from the MIX database (Li *et al.*, 2017),

Fig. 1. Four domains of nested grids used for the Air Quality Model.

Table 1. Emission database for CMAQ.

Area	Anthropogenic emissions	Biological emissions
East Asia	MIX database	EABEIS
China	MEIC-2012	EABEIS
Taiwan	TEDS-9.0	TBEIS

while biological emissions were obtained using the East Asia Biogenic Emission Inventory System (EABEIS), which applies meteorological data to estimate hourly emissions (Chen *et al.*, 2013). China's MEIC-2012 (Multi-resolution Emission Inventory for China) database was used as the source of information on anthropogenic emissions (Qin *et al.*, 2018).

The year 2012 was used as the base for estimation, and then the test was adjusted to the 2013 emissions. As for Taiwan's emission data, the anthropogenic source emission data was the TEDS-9.0 (the estimated base year was 2013), and the biological source emissions were coordinated by the Taiwan Emission Inventory Emission System (TBEIS) (Hsu and Cheng, 2016). Meteorological data were applied to estimate the hourly emissions (Chang *et al.*, 2009a; Chang *et al.*, 2009b). In addition, both the initial and boundary conditions must be set for the grid mode simulation (Samaali *et al.*, 2009). The initial and boundary condition processing procedures used in this study come from a set of hypothetical or experimental data, which typically do not match the actual situation. To reduce the error caused by the approximated initial and boundary conditions, the simulation is typically run several days prior to the period of interest (Arnold *et al.*, 2003; Wong *et al.*, 2012).

CMAQ Base Model Performance Evaluation

The CMAQ model was used for the benchmark case simulation in this study while the CMAQ-DDM (Community Multi-scale Air Quality with Decoupled Direct Method) was used for the simulation of the various industrial categories to explore the key PM_{2.5} sources in Tainan City and its neighboring counties and cities. The decoupling direct method (DDM), which is a sensitivity calculation module in the CMAQ, was applied to indicate the sensitivity of specific parameters while performing general CMAQ simulation operations (Appel *et al.*, 2008). The sensitivity equations captured the effects of changes in certain parameters on PM_{2.5} concentrations and then aggregated the sensitivity of the PM_{2.5} concentrations for multiple parameters. Repeating this procedure for different regions provided the PM_{2.5} sensitivity at each designated area (Foley *et al.*, 2010).

The CMAQ-DDM uses a nested grid simulation for which the range is equal to the one applied for the baseline case, covering the entire East Asia region, taking into account the effects of PM_{2.5} from East Asia, and reducing the impact of boundary settings (Appel *et al.*, 2008). In this study, the CMAQ without the DDM module was applied to simulate the first to the third domain; the simulation results from the third domain were then applied as the boundary and initial conditions for the fourth domain. In the fourth domain simulation, the CMAQ with the DDM

module was applied (Foley *et al.*, 2010). The simulation case and calculation method used in this study were divided into a single baseline case and model simulations of 12 emission categories, as shown in Table 2. During the study, both qualitative and quantitative analyses were done whereby (1) the qualitative analysis was done by plotting the spatial concentration distribution of selected pollutants to understand impact of pollution distribution on a given space, and (2) a quantitative analysis was done on the concentration of pollutants within the stations in Tainan City (excluding traffic stations). The contribution and impact ratio of each emission source of the selected pollutants was applied to represent the impact of the 12 pollution sources on the air quality within Tainan City (Wong *et al.*, 2012).

RESULTS AND DISCUSSION

Analysis of Emissions

The spatial distribution of pollutant emissions and the simulation results were analyzed for the benchmark case. The spatial distribution of pollutant emissions from Domain 4 in Taiwan and the scope of this project (Tainan City) are shown in Fig. 2. The chemical species of interest included PM_{2.5}, SO_x, NO_x, NH₃, and NMHC. From the perspective of the spatial distribution of the emissions, the overall PM_{2.5}, SO_x, NO_x, NH₃, and NMHC have relatively high emission sources in the western part of Taiwan (Shih *et al.*, 2009; Hsu *et al.*, 2016). In terms of species, high primary PM_{2.5} emissions have been observed in the three metropolitan areas located in the northern, central, and southern parts of Taiwan (Chao *et al.*, 2014). In the eastern region, higher emissions of PM_{2.5} have been observed in Yilan County and Huadong Rift Valley; while in Tainan City, the emissions in the southwestern urban areas have been found to be higher than in other parts of the city (Chen *et al.*, 1999; Fang *et al.*, 2003). Most SO_x emissions have been found to be distributed in industrially developed areas, such as Taoyuan, southwestern Taichung, and Kaohsiung. The distribution of SO_x emission sources in Tainan City have been found to be relatively scattered, and are mostly located near Xinhua in Tainan City and in new urban areas (Lin and Lin, 2002; Yen and Horng, 2009). Transportation activities are the main sources of NO_x, so high emissions have been observed in metropolitan areas with high traffic flow and highways (Chang *et al.*, 2014). One of the areas of Tainan City with notably high NO_x emissions is the region surrounding National Highway No. 1 (Akimoto and Narita, 1994; Lin and Wu, 2003). The main source of NH₃ emissions is agriculture and animal husbandry. Consequently, the emission of NH₃ in the central southern part of Taiwan is significantly higher as compared to other regions. NH₃ emission sources are concentrated in the western part of Tainan, and the emission rates have been shown to exceed other regions by approximately 2 to 6 g s⁻¹ (Hsieh and Chen, 2010). NMHC has been shown to have more emission sources in the metropolitan area of Tainan, for which the emission rates have been shown to range between 14 and 16 g s⁻¹. In addition, due to the contributions of emissions from biological sources (plants),

Table 2. Modeling case definition and calculations.

Pollutant source	Case definition (Effects of emission sources on Tainan's air quality)	Calculation (model simulation categories simulated against the baseline case-A)
Tainan	Chemical manufacturing plants	Base case (A) vs. Case of non-chemical material manufacturing emissions in Tainan (B)
	Iron and steel manufacturing	Base case (A) vs. Case of non-Iron and Steel Manufacturing emission in Tainan (C)
	Power plants	Base case (A) vs. Case of non-Power industry emission in Tainan (D)
	Manufacturing of coal-based products	Base case (A) vs. Case of non-iron and steel manufacturing emissions in Tainan (C)
	Mobile sources (diesel vehicles)	Base case (A) vs. Case of non-power industry emissions in Tainan (D)
	Two-stroke scooters	Base case (A)-Case of non-coal product manufacturing emissions in Tainan (E)
	Catering services	Base case (A) vs. Case of non-diesel vehicle emissions in Tainan (F)
	Construction/road dust emission	Base case (A) vs. Case of non-two-stroke scooter emissions in Tainan (G)
	Open burning of waste	Base case (A) vs. Case of non-catering emissions in Tainan (H)
	Taichung power plant's	Base case (A) vs. Case of non-construction and road dust emissions in Tainan (I)
Outside Tainan	Sixth Naphtha (Yunlin)	Base case (A) vs. Case of non-open burning emissions in Tainan (J)
	Dragon steel company	Base case (A) vs. Case of non-Taichung Power Plant emissions (K)

Fig. 2. The spatial distribution of base case emissions in (a) Taiwan and (b) Tainan City for the year 2013 (D4).

NMHC emissions are scattered throughout Taiwan (Chang *et al.*, 2009b). Tainan City has significantly higher emission sources of NMHC in the southwestern regions as well as in the eastern mountainous areas. NMHC sources in most of the urban areas are commercial activities while in the mountains they are mainly from vegetation (Hwa *et al.*, 2002; Li and Hou, 2015).

Benchmark Case Simulation Results

Simulations were carried out with reference to cases in the following months; January, April, July, and October of 2013, after which the spatial distribution of pollutant concentrations was analyzed. The spatial distribution of the monthly mean concentration of each pollutant (Domain 4) is shown in Fig. 3. The concentration of PM_{2.5} was the

highest in January, followed by October, and was the lowest in July. Regionally, PM_{2.5} concentrations in the western side of Taiwan are higher than in other regions (Chen *et al.*, 2013). In January and October, the concentration in the central southern part of Taiwan was significantly higher, as opposed to the concentration during the month of April, whereby the concentration of the emissions in the northern part of Taiwan were as high as 39 $\mu\text{g m}^{-3}$. In July, there were higher concentrations in the three metropolitan areas of North, Central and South, with the highest concentration in Xinbei City, where the concentration of PM_{2.5} ranged between 27 $\mu\text{g m}^{-3}$ and 33 $\mu\text{g m}^{-3}$.

The concentration of NO_x exceeded 13.5 ppb in the three metropolitan areas and the central southern highway sections (Changhua, Nantou, Yunlin, and Chiayi). The NO_x

Fig. 3. The spatial distribution of mean monthly concentrations of air pollutants in January, April, July, and October for the year 2013.

concentrations in these areas showed different trends. In the central and southern parts of Taiwan, the concentration was highest in October; while the concentrations in the northern, central, and southern region of Taiwan was highest in April (Lin and Wu, 2003). In the month of July, the concentration was higher in the northern region as compared to other areas.

During the four months considered for this study, SO_2 had a high concentration on the coasts of Taichung, Yunlin, and Kaohsiung, with concentrations as high as 7 ppb. The location with the highest concentrations shifted during the four seasons. On the coast of Kaohsiung, the region of high concentration had the widest spread in the month of October, while for Taichung and Yunlin coasts,

the high concentration zones stretched the widest in July and October as compared to in January and April (Akimoto and Narita, 1994).

According to the results, the concentration of NH_3 in Taiwan was highest in regions lying in the south of Taichung as compared to other parts of Taiwan. Among them, Pingdong County had the highest concentration, which exceeded 60 ppb, followed by Zhanghua and Yunlin. In July, the concentration of NH_3 in Zhanghua County exceeded 60 ppb, while the highest concentration of NH_3 in Yunlin County in October fell in the range of 32 ppb and 56 ppb. This could be attributed to changes in farming activities as well as meteorological conditions (Jiménez *et al.*, 2007).

The highest concentrations of NMHC were observed in January, followed by October and April. Regionally, NMHC concentrations in the three major metropolitan areas in Taiwan were higher than in other regions, with Taipei, New Taipei, and Taoyuan having the highest concentrations. The regions with the highest concentration for the month of January were mostly in Taichung and Kaohsiung cities and exceeded 210 ppb. For the four months under investigation, the range of the regions with high concentrations differed greatly. The region of maximum NMHC was the largest in January compared to other months, and the overall concentration in the southwestern part of Taiwan exceeded 135 ppb. Even though the NMHC concentration in July still exceeded 135 ppb, it was narrowly distributed in the urban areas (Yen and Horng, 2009).

The spatial distributions of the mean monthly concentrations of the pollutants of interest indicated that the $\text{PM}_{2.5}$, NO_x , and NMHC species had a highest ambient air concentrations in January; NH_3 had the highest concentration in July, and SO_x had its highest ambient air concentration October (Yen and Horng, 2009).

Spatial Distribution of Emissions from Different Sources

The spatial distributions of the specific emission sources discussed in this study are shown in Figs. 4 and 5, which are the pollution sources within Tainan City and the pollution sources in the neighboring counties and cities (including the Taichung Power Plant, the Sixth Naphtha, and the Dragon Steel Company). Based on the spatial distribution of various pollution sources in Tainan City shown in Fig. 4, most of the emission sources, for example, chemical manufacturing plants, iron and steel factories, and coal-fired factories, were located in the new and new urban areas of Tainan City (Chang et al., 2018). There were also obvious sources of emissions in the southwestern part of Tainan, where the steel industry has sporadic sources of emissions in the western part of Tainan City. The distributions of emissions from diesel vehicles exhibit linear distributions, which is consistent with the expressway routes. The emissions from two-stroke engines were distributed throughout Tainan City, with higher emissions in the southwestern region of Tainan's urban area. Unlike diesel vehicles, the distribution of emissions from two-stroke engines for various species covered a wider geographical area. In addition, the NMHC emissions were higher than those of diesel vehicles, indicating that the two-stroke engines on the roads contribute significantly to NMHC emissions. The spatial distribution of catering, construction/road dust, and open burning combustion emissions was widely distributed (Lang et al., 2017). The catering industry and construction/road dust emissions were mostly concentrated in the urban areas of southwestern Tainan, while open burning was the more obvious emission in the northern region of Tainan City (Chen et al., 1999; Lin et al., 2006).

From the spatial distribution of the emissions from sources in the neighboring counties and cities shown in Fig. 5, Taichung Power Plant and the Sixth Naphtha and Dragon Steel Company can be represented as point source emissions, where their emissions are mostly distributed in

the locations of the respective plants. It can be seen that the main emissions from the Taichung power plant are $\text{PM}_{2.5}$, NO_x , and SO_x ; those from the Sixth Naphtha Company are NO_x , SO_x , and NMHC, and those from the Dragon Steel Company are NO_x and SO_x .

Effects of Different Pollution Sources on Tainan City's Ambient Air Quality in Terms of $\text{PM}_{2.5}$ Concentration

Chemical Manufacturing Plants

Fig. 6(a) shows the spatial distribution of the monthly average $\text{PM}_{2.5}$ contributions from chemical manufacturing plants in Tainan. The figure shows that the chemical manufacturing plant emissions by month and year mainly affect the ambient air in the southwestern part of Tainan and the central region (Chen et al., 2019). The high-impact regions had $\text{PM}_{2.5}$ concentrations that increased from $0.18 \mu\text{g m}^{-3}$ at the outermost region towards the source center. In addition, emissions from the chemical manufacturing plants spread to the Kaohsiung or Pingtung areas during the months of January, April, and October according to changes in the weather. The amount of pollutant dispersion was highest in the month of January. The size of the source in the summer as represented by the month of July had an impact ratio of 0.9%, which was the highest among all four seasons (Appel et al., 2008). This is partly due to the favorable conditions for the dispersion of pollutants in Taiwan and the low levels of emissions transported into Taiwan from overseas. Therefore, the concentration of $\text{PM}_{2.5}$ was significantly lower in July as compared to other seasons due to dispersion resulting in an increase in the impact ratio (Chen et al., 2013).

Iron and Steel Industry

The spatial distribution of the impact of steel industry emissions on the monthly average $\text{PM}_{2.5}$ concentrations in Tainan for the year 2013 is shown in Fig. 3(b). The results in the figure show that the steel industry emissions mainly affected the middle region of Tainan City in all the months considered during the study period (Lin et al., 2006). The amount of influence in the north was higher, and the highest impact concentration exceeded $0.30 \mu\text{g m}^{-3}$. In addition, the impacts of the steel industry emissions were greatly affected by prevailing weather conditions. The range of the influence caused in January was the widest among all the months under consideration, and the impact extended to the Kaohsiung area (the impact was about $0.18\text{--}0.22 \mu\text{g m}^{-3}$). The proportion of the sources varied, with the highest variation exceeding 1.5% in the month of July.

Power Plants

The spatial distribution of the impact of power industry emissions on the average monthly concentration of $\text{PM}_{2.5}$ in Tainan is shown in Fig. 7(a). The figure shows that the emissions from power plant in the months under investigation extended southwards in the central Tainan, with the farthest point reached being Kaohsiung and Pingtung. The high-impact areas had concentrations exceeding $0.14 \mu\text{g m}^{-3}$. The range of influence varied from one season to another, with the most extensive impact range in January, affecting

Fig. 4. The spatial distribution of pollutant concentrations for each emission source in Tainan City for the year 2013 (D4).

Fig. 5. The spatial distribution of pollutant concentrations for emission sources outside Tainan City in 2013 (D4).

the Pingtung area, where the highest concentration exceeded $0.23 \mu\text{g m}^{-3}$. However, for the months of July and October, the emissions mainly affected the ambient air in Tainan City. The area affected by the emissions exceeded 0.5% of the total area of Tainan City for the entire year, and the impact ratio in January and July in each season was also relatively higher compared to that of April and October. In all affected stations within Tainan City, the average concentration for the year was $0.09 \mu\text{g m}^{-3}$, of which the highest impact was in January with $0.12 \mu\text{g m}^{-3}$ and lowest in July (Zhang *et al.*, 2018). It can be seen in Fig. 7(a) that there were significant variations in the amount of influence from the spatial distribution for the time periods under investigation. The power stations in Tainan City (Xinying, Annan, and Tainan stations) were far away from the regions most affected by the emissions.

Manufacturing of Coal-based Products

The contribution of the emissions from the application of raw coal in the synthesis of other products based on the mean monthly $\text{PM}_{2.5}$ concentration in Tainan is shown in Fig. 7(b). The effects of the emissions in all the months

under investigation were most intense in the central region of Tainan City (Fang *et al.*, 1999). The maximum contribution was slightly above $1.5 \mu\text{g m}^{-3}$, and the area coverage of the impact in all seasons was relatively the same. In the region of interest, the impact of the emissions slightly exceeded 3.0% in all months under consideration; and the range of the affected area during the month of July was wider compared to other seasons. The additional average annual contribution from this source was $0.25 \mu\text{g m}^{-3}$, with the highest impact in the month of July ($0.34 \mu\text{g m}^{-3}$) and the lowest in January. The average annual impact ratio from this emission source was 0.8%. The highest impact ratio was in the month of July, which was 2.3%, and the lowest was in January.

Diesel Vehicles

Fig. 8(a) shows the effect of spatial distribution of monthly emissions diesel vehicles on the monthly mean $\text{PM}_{2.5}$ concentrations in Tainan. From the figure, the total emissions of diesel vehicles for each month and the annual average affected the entire area of Tainan City. The impact was the highest along the highway section, where it

Fig. 6. The spatial distribution of $PM_{2.5}$ concentrations from (a) chemical manufacturing plants and (b) the iron and steel industry.

Fig. 7. The spatial distribution of $PM_{2.5}$ concentrations from (a) power plants and (b) manufacturing of coal-based products.

Fig. 8. The spatial distribution of $PM_{2.5}$ concentrations from (a) diesel Vehicles and (b) two-stroke scooters.

exceeded $1.5 \mu\text{g m}^{-3}$. The differences among the months considered in this study were mainly due to variations in the concentrations of $\text{PM}_{2.5}$ as well as the range. Among them, the highest concentration (in excess of $1.5 \mu\text{g m}^{-3}$) in October had the widest range of dispersion, which covered all of Tainan City (Yang *et al.*, 2017b). The impact of the emissions from diesel vehicles was lowest in the month of July, and was limited to the expressway and surrounding areas. In addition, the impact of emissions from diesel vehicles extended to the Kaohsiung area, due to the strong northeast monsoon in January, April, and October (Chuang *et al.*, 2018). The region surrounding main high roads was greatly affected, with the impact ratio exceeding 4.5% in all seasons; the highest dispersion of the impact ratio was in the month of July.

Two-stroke Engines

The spatial distribution of the impact of emissions from two-stroke engines on the monthly average $\text{PM}_{2.5}$ concentration in Tainan is shown in Fig. 8(b). Just like for diesel vehicles, two-stroke engine emissions for all months under investigation as well as the average annual concentration values covered the entire Tainan City area (Seneviratne *et al.*, 2017). The concentration of emissions in the eastern part of the country was highly influenced by the emissions from the urban area in the southwestern part of Tainan. The average annual concentration ranged between 1.5 and $0.21 \mu\text{g m}^{-3}$. The trend of the emissions in the month of January, April, and October were fairly similar, with a concentration exceeding $0.20 \mu\text{g m}^{-3}$ in October, and the influence of this emission source on the western part of Tainan was significantly high (Chernyshev *et al.*, 2018). The distribution of the impact ratio was similar to distribution of the concentration of the pollutant. The average annual impact ratio was about 0.6–0.7%. The highest impact ratio was during summer while the lowest was in winter.

Catering Industry

The spatial distribution of the impact of emissions from the catering industry on the monthly average concentration of $\text{PM}_{2.5}$ in Tainan City is shown in Fig. 9(a). It can be seen from the figure that the scope of the catering industry emissions was mainly distributed in the urban area of the southwestern part of Tainan City. The maximum annual average concentration was more than $0.75 \mu\text{g m}^{-3}$. The distribution patterns of the emissions were similar for all months across the year except for January, when the emissions spread southwards towards Kaohsiung, with the greatest impact of emissions occurring in the months of April and October for Tainan City (Niyobuhungiro and von Blottnitz, 2013). The southwestern winds during the summer appeared to affect the catering industry's emissions for the month of July, where the emissions were dispersed towards the northeastern side of Tainan City. The annual average impact ratio for the entire year exceeded 3.0%, with the summer season having the widest range of influences among all seasons, where the affected proportions in the western part of Tainan were over 1.8% of the total area coverage.

Construction/Road Dust

The spatial distribution of the impact of construction/road dust emissions is shown in Fig. 9(b). The figure shows that the emissions impacted all of Tainan City, with the highest concentrations in the southwest and central areas of Tainan City (Karanasiou *et al.*, 2011; Pant and Harrison, 2013). The average annual concentration for the year under study ranged between 0.9 and $1.2 \mu\text{g m}^{-3}$. Among all months under consideration, January had the widest range of influence, which spread all the way to the south, while July had the highest concentration ($1.2\text{--}1.5 \mu\text{g m}^{-3}$). The total impact ratio for the entire year was over 3.75%. The proportion of influence was the highest in July, and the affected proportion of Tainan City exceeded 4.5%.

Open Burning

The spatial distribution of the effects of open-air combustion emissions is shown in Fig. 10(a). The figure shows that the impact range was mainly in the eastern part of Tainan City, with the highest impact ratio slightly exceeding $0.33 \mu\text{g m}^{-3}$ (Martins *et al.*, 2018). It can be seen that there was no contribution of $\text{PM}_{2.5}$ from open-air burning in the month of January; whereas April had the highest contribution of all four months, with the highest impact exceeding $1.5 \mu\text{g m}^{-3}$. The impacts in July and October were barely significant, and the spatial distribution was mainly affected by the Houbi, Xinying, and Liuying areas (Chi *et al.*, 2016; Chang *et al.*, 2018). The average annual impact ratio was as high as 1.5%. The dispersion of the emissions was widest in the month of April among all seasons, and the impact ratio rose up to a maximum of 4.5%.

The Taichung Power Plant

The spatial distribution of the impact of the Taichung Power Plant emissions is shown in Fig. 10(b). The figure shows that the impact range was mainly in the western part of Tainan City, with the highest impact in Qigu and Annan districts, with a range of 1.0 to $1.1 \mu\text{g m}^{-3}$. It can be seen in each month that the degree of influence was highest and the most extensive in January, where concentration exceeded $1.5 \mu\text{g m}^{-3}$ slightly, followed by the degree of influence and concentration in month of October. It should be noted that the impact of Taichung Power Plant emissions peaked in Tainan City for the total annual average and in the month of October, which may have been due to the reaction of NH_3 emissions from Tainan City and the $\text{PM}_{2.5}$ precursors discharged from the Taichung Power Plant (Lin *et al.*, 2006). The annual average impact ratio ranged between 3.6% and 4.2%. The emissions were dispersion most for the months of January and July, where the impact ratio was as high as 4.5%.

The Sixth Naphtha

The spatial distribution of the impact of the emissions from the Sixth Naphtha is shown in Fig. 11(a). From the annual average impact, the effect of the emissions appeared to be dominant in the North Gate, General, and Qigu districts on the western coast of Tainan City, with the highest impact in the Beimen District, which ranged between

Fig. 9. The spatial distribution of $PM_{2.5}$ concentrations from (a) catering and (b) construction/road dust.

Fig. 10. The spatial distribution of $PM_{2.5}$ concentrations from (a) open air burning of waste and (b) Taichung Power Plant.

Fig. 11. The spatial distribution of $PM_{2.5}$ concentrations from (a) the Sixth Naphtha and (b) the Dragon Steel Company.

Table 3. The concentrations of PM_{2.5} in Tainan City for the year 2013.

Emission sources	January	April	July	October	Annual (4 months average)	
Unit	$\mu\text{g m}^{-3}$	$\mu\text{g m}^{-3}$	$\mu\text{g m}^{-3}$	$\mu\text{g m}^{-3}$	$\mu\text{g m}^{-3}$	%
Base case	41.61	31.33	14.94	37.95	31.38	31.38
Chemical manufacturing plants	0.09	0.11	0.14	0.16	0.12	0.4
Iron and steel industry	0.15	0.15	0.12	0.16	0.14	0.5
Power Industry	0.12	0.08	0.06	0.11	0.09	0.3
Manufacturing of coal-based products	0.15	0.23	0.34	0.28	0.25	0.8
Diesel vehicles	0.89	0.92	1.01	1.39	1.06	3.4
Two-stroke scooters	0.13	0.14	0.16	0.17	0.15	0.5
Catering	0.49	0.54	0.58	0.60	0.56	1.8
Construction/road dust	0.72	0.72	0.91	0.84	0.80	2.5
Open burning	0.00	0.22	< 0.01	0.01	0.06	0.2
Taichung power plant	1.38	0.87	0.25	1.00	0.87	2.8
Sixth Naphtha Cracking Complex	0.32	0.55	0.35	0.37	0.39	1.3
Dragon steel company	0.37	0.24	0.04	0.20	0.21	0.7
Total	4.80	4.76	3.97	5.30	4.70	15.0
Other sources	36.81	26.57	10.97	32.65	26.67	85.0

0.5 and 0.7 $\mu\text{g m}^{-3}$. From the impact ratio for the months under consideration, the impact of the Sixth Naphtha emissions in April was the highest and the most widespread; the impacts in the North Gate, General, and Qigu districts exceeded the maximum of 0.75 $\mu\text{g m}^{-3}$, and the lowest dispersion range and concentration occurred in July. The annual average impact ratio ranged between 1.5% and 2.7% on the western coastal areas of Tainan (Chang *et al.*, 2018). The overall impact ratio for the Sixth Naphtha in Tainan City was more than 2.25%, with the highest portion affected in the eastern part of Tainan, with an impact ratio of between 2.75% and 3.25%.

The Dragon Steel Company

The spatial distributions of the emissions from the Dragon Steel Company are shown in Fig. 11(b). The figure shows that the impact range was mainly in the western part of Tainan City, and the affected surface area reduced from north to south. The annual average had the highest concentration, ranging between 0.24 and 0.28 $\mu\text{g m}^{-3}$. For all the months under investigation, January had the highest impact and the widest range. The western coastal areas of Tainan had the highest impact, which ranged between 0.40 and 0.48 $\mu\text{g m}^{-3}$. The extent of the emissions' of dispersion for the months of April and October were fairly comparable, even though the impact in April was significantly higher (Chi *et al.*, 2013). The annual average impact ranged between 0.9 and 1.0% mostly in Beimen District, and the degree of influence in January and April was wider as compared to July and October with the highest impact rate in January ranging between 1.3 and 1.5%.

CONCLUSIONS

According to the spatial distribution of emissions resulting from various pollution sources, the pollution sources in Tainan City mainly affect the ambient air in Tainan City, with the exception of the chemical manufacturing industry and the power industry. The external sources of pollution

(outside the city) mostly affected the western part of Tainan City, which is mostly a coastal region due to existing meteorological factors. PM_{2.5} precursors emitted within Tainan City may react with the precursors emitted in other counties and cities to produce PM_{2.5}, which might impact the ambient air quality in Tainan City. Therefore, besides controlling the emission of primary PM_{2.5}, the emission of precursors for fine particulate matter requires regulation strategies as well.

According to the annual results of emissions from the 12 sources of pollution, as shown in Table 3, the impact of diesel vehicle emissions was the highest (1.06 $\mu\text{g m}^{-3}$), followed by the impact of the Taichung Power Plant emissions (0.87 $\mu\text{g m}^{-3}$) and the impact of construction/road dust emissions (0.80 $\mu\text{g m}^{-3}$), while the lowest impact was from open-air combustion emissions. The order of the impact ratio for the 12 pollution sources under study is the same as the concentration of PM_{2.5} they emitted. The three pollution source categories i.e., diesel vehicles, Taichung power plants and construction/driving dust emissions, had their impact ratios as 3.4%, 2.8% and 2.5% respectively. The total impact ratio of the 12 industries under study was 15.0% and 85.0% for the PM_{2.5} sources within Tainan City and those outside Tainan city, respectively. In order to draw a full picture of the state of pollution caused by fine particulates in Tainan, further studies on sources of fine particulate matters should be conducted in Tainan, which may include Tainan City pollution sources not covered in this study as well short range and long range transportation of fine particulates from other neighboring counties, cities, and even countries.

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